LAMB SHIFT POLARIMETER FOR A HELIUM-3 ION BEAM

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The principle of the Lamb shift polarimeter intended for polarization measurement of ^{3}He ions emerging from the polarized ion source is described.

The principle of the polarimeter is based on the $2S_{1/2}$– $2P_{1/2}$ energy difference (Lamb shift) and the dependence between the nuclear spin polarization of ^{3}He ions and the populations of the hyperfine levels of the $2S_{1/2}$ metastable state of $^3He^+$ ions, which are produced in the electron transfer processes

$$^3\mathrm{He}^{++} + \mathrm{X} \rightarrow ^3\mathrm{He}^+(2\mathrm{S}) + \mathrm{X}^+, \qquad (1)$$

$$^3\mathrm{He}^{+} + \mathrm{X} \rightarrow ^3\mathrm{He}^+(2\mathrm{S}) + \mathrm{X}. \qquad (2)$$

The process (2) may be suitable for measuring the nuclear polarization in the polarized ion source using the method of "electron pumping". [1] As X, it is possible to use different gases, including air. [2,3] This method is similar to the one developed earlier for protons and deuterons. [4–7] There is a difference: instead of atoms we have charged ions, so, at low energies it is impossible to apply a transverse electric field for quenching the metastable states. It is proposed to use a longitudinal electric field at the second crossing of the levels βf (mixing with $\Delta m_J = 0$). The labels for the levels follow the usage of Lamb and Retherford. [8]

The relative populations of the four $2S_{1/2}$ hyperfine sublevels $N(F, m_F)$ of $^3He^+$ ions after the electron transfere processes (1,2) are as follows: $N(0,0) = (1 - P_z x/\sqrt{1+x^2})/4$, $N(1,1) = (1 + P_z/4)$, $N(1,0) = (1 + P_z x/\sqrt{1+x^2})/4$, $N(1,-1) = (1-P_z)/4)$, where $x = B/B_c(2S_{1/2})$, $B_c(2S_{1/2})$=387 G, the critical field for the $2S_{1/2}$ state.

In the absence of any fields, the lifetime of the metastable state is equal $\tau_{2S} = 2 \times 10^{-3}$ s. An electric field induces the Stark effect and the lifetime of the $2S_{1/2}$ state diminishes. If an electric field E is perpendicular to an magnetic field B, the allowed mixings of the levels are those with $\Delta m_J = \pm 1$, that is, $\alpha - f$ and $\beta - e$; if E is parallel to B, the allowed transitions are $\alpha - e$ and $\beta - f$. The lifetimes of the perturbed states are [8]

$$\tau_{2S} = \tau_{2P}[\nu^2 + (4\pi\tau_{2P})^{-2}]h/|V|^2, \qquad (3)$$

where $\tau_{2P} = 10^{-10}$ s, $h\nu$ is the energy difference between the levels involved in the transitions, and V is the electric dipole matrix element. At the level crossing

$$\tau_{2S} = h/16\pi^2 \tau_{2P} |V|^2. \tag{4}$$

Let a beam of metastable helium ions goes through a magnetic field coresponding the level crossing in an electric field, so chosen that only small quantity of the ions in the α state decayes, while practically all the ions in the β state are quenched to the ground state. The population of the α state is the function of nuclear polarization of the primary helium ions:

$$N(\alpha) = N(0,0) + N(1,1) = (1/2)[1 + P_z(1 - x/\sqrt{1+x^2})/2]. \tag{5}$$

The flow of ions in α state is proportional to its population. So, if we measure this flow for the case of zero polarization (I_0) and for polarized beam (I_+), the polarization equals

$$P_z = \frac{2}{1 - x/\sqrt{1+x^2}} (\frac{I_+}{I_0} - 1). \tag{6}$$

Reversing the magnetic field direction in the gas region and the quenching region, it is possible to change the sign of polarization. The counts of the 41 eV photons are I_+ and I_- in this case. Then the projection of nuclear polarization of the primary beam on the direction of the magnetic field in the polarimeter (before reversal) is

$$P_z = \frac{2}{1 - x/\sqrt{1+x^2}} \frac{I_+ - I_-}{I_+ + I_-}. \tag{7}$$

First crossing (βe) takes place at $B \approx 0.75$ T. In this case, E must be perpendicular to B, $\nu(\alpha - f)$=28 GHz, $\tau_\beta = 4.91 \times 10^{-5}/E^2$, $\tau_\alpha = 6.76 \times 10^{-2}/E^2$, ratio – 1380. If L is the length of the magnetic field region, v – the velocity of ions, $t = L/v$ – the time of interaction, the parameter ζ defines the quenching the β-state, $\exp(-t/\tau_\beta) = 10^{-\zeta}$, the parameter δ defines the quenching the α-state, $\exp(-t/\tau_\alpha) = \delta$, W(keV) – the energy of ions, then the demanded electric field in V/cm and δ are

$$E = 57\sqrt{\zeta/L} \times \sqrt[4]{W},\ \delta = 1 - 1.7 \times 10^{-3}. \tag{8}$$

Example: if W=20 keV, L=20 cm, ζ=3, then E=47 V/cm.

Second crossing (βf) takes place at $B \approx 1.5$ T. Here $E \| B$, $\nu(\alpha - e)$=28 GHz, $\tau_\beta = 4.33 \times 10^{-5}/E^2$, $\tau_\alpha = 8.16 \times 10^{-2}$, ratio – 1880. With U=EL

$$U = 50\sqrt{\zeta L} \times \sqrt[4]{W},\ \delta = 1 - 1.3 \times 10^{-3}. \tag{9}$$

Example: for W=20 keV, ζ=3, L=20cm, we have U=820 V.

For final quenching of the α state with transverse electric field E (B=0), accepting $\exp(-t/\tau_{2S}) = 10^{-\epsilon}$,

$$E = 970\sqrt{\epsilon/L} \times \sqrt[4]{W}. \tag{10}$$

Example: 1) W=20 keV, L=10cm, ϵ=1, E=650 V/cm; 2) W=10 keV, L=10 cm, ϵ=1, E=550 V/cm.

There is another possibility, which may be seen from the paper by Burcham et al.,[2] to quench the β state: the use of rf field $\approx$ 10 GHz at $B \approx 0.2$ T. Of course, this idea may be applied for protons and deuterons. The magnetic field need not be very homogeneous; that is an important advantage comparatively with spin filter polarimeter.[9]

For hydrogen, using rf field with frequency 1147 MHz permits to quench the state $2S_{1/2}(F = 1)$ through the transition to $2P_{1/2}(F = 0)$ (at essentially zero magnetic field), keeping the state $2S_{1/2}(F = 0)$ with population $N(0,0) = (1+P_z x/\sqrt{1+x^2})/4$, which can be measured by quenching with static electric field. The feasibility of such polarimeter followes from the results of early paper by Boyd et al.[10] For deuterons or helium ions, this method is unacceptable due to the natural width of levels.

In conclusion, it is necessary to point that the polarimeter, in fact, measures the projection of nuclear polarization P_z on the direction of magnetic field in the polarimeter.

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